

Field Investigation of Indoor Thermal Environments in Traditional Chinese Shophouses with Courtyards in Malacca

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Abstract

This study investigates indoor thermal conditions in traditional Chinese shophouses (CSHs) in Malacca, Malaysia, using field measurements and focuses on the cooling effects of courtyards. The results indicate that the indoor air temperature in the living rooms of CSHs was approximately 5-6°C lower than the outdoor temperature during the day primarily due to structural cooling effects with night ventilation, whereas the indoor air temperature at night was similar to the outdoor temperature. If the thermal adaptations of the occupants were considered, then the thermal conditions in the living rooms were acceptable for most of the day. The results indicate that the front courtyards functioned as a cooling source for the surrounding spaces in the CSHs.

Keywords: Chinese shophouse; thermal comfort; vernacular architecture; courtyard; passive cooling

1. Introduction

Energy savings are important in the global building sector due to concerns about the availability of energy and effects of global warming. In terms of passive design, recent studies have investigated traditional techniques used in vernacular architecture to determine potential solutions for achieving sustainability in modern buildings (e.g., Upadhyay *et al.*, 2006; Park and Park, 2010). These techniques are worth considering because vernacular architecture has withstood the test of time and, more importantly, was developed in response to experiences with conditions and use (Oliver, 2006).

The goal of this study is to understand traditional passive cooling techniques used in and around vernacular architecture in Malaysia and apply them to modern urban houses. Two major types of vernacular houses can be found in Malaysia, the Malay house and the Chinese shophouse. The authors have previously studied thermal comfort levels in traditional Malay houses based on field measurements (Toe and Kubota, 2013). The Malay house is typically a well-ventilated detached building that consists of a timber structure

with a raised floor. The Chinese shophouse (CSH) is essentially an elongated brick row house that is located in relatively dense urban areas.

The origin of CSHs can be traced back to the influx of Chinese immigrants from densely populated southern coastal provinces of China in the 19th century until World War II (Chen, 1998). By the early 20th century, this urban design spread to every major town in Malaysia. One of the most important features of CSHs is the courtyard. Originally, interior courtyard houses were typically found in residences throughout China, but their composition and scale were different across the country (Knapp, 1999). In general, the proportion of courtyards to structural space diminishes significantly from northeast to southeast China to restrict the infiltration of direct solar energy and to facilitate ventilation (Knapp, 1999). Therefore, Knapp used the term '*skywell*' to describe a relatively small courtyard, which is typical of those found in southeast China, as opposed to a relatively large northern courtyard. Most of the courtyards in Malaysian CSHs are considered to be '*skywells*' in terms of their configuration and functionality. However, because '*skywell*' is a substitution for the corresponding Chinese word, the term 'courtyard' will be used in this paper.

Courtyard houses can be found not only in China or Southeast Asia but also in many other parts of the world (Edwards *et al.*, 2006). Previous studies have been conducted on courtyard houses and their thermal effects, but most of these studies were conducted in hot, dry climates (Al-Hemiddi *et al.*, 2001; Berkovic *et al.*,

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2012), and some studies were conducted in hot, humid climates. Some of the studies that were conducted in tropical climates include Rajapaksha *et al.* (2002, 2003), Tablada *et al.* (2009) and Dili *et al.* (2011). For example, Rajapaksha *et al.* (2003) investigated the potential use of a courtyard for passive cooling in a single-storey high-mass building located in the warm, humid climate of Colombo, Sri Lanka. These studies provided significant insight into courtyard design in the tropics, but most of them focused on detached houses, which are different from CSH row houses. Unlike detached houses, an elongated row house typically only has a few openings, and thus, its indoor thermal conditions are significantly different.

This paper investigates indoor thermal conditions in traditional CSHs located in Malacca, Malaysia, by using field measurements and focusing on the cooling effects of courtyards. The resulting measurements will be compared to measurements that were obtained in modern Malaysian terraced houses in 2007 (Kubota *et al.*, 2009). Similar to the CSHs, these terraced houses are constructed of brick outer walls and elongated row houses. Therefore, the traditional passive cooling techniques used in CSHs should be applicable to modern terraced houses.

2. Methods

Field measurements were obtained from 12 October 2011 to 17 October 2011 in two adjacent Chinese shophouses (CSHs) located at a Malaccan heritage site (Figs.1.-2.). Malaysia has nearly uniform climate conditions throughout the year (except for wind and rainfall patterns due to monsoons). For example, the mean monthly air temperature at the Malacca weather station ranged from 26.5-27.8°C for a small variation

of 1.3°C over the last three decades (JMA, 2013). The two CSHs were originally constructed in the Dutch colonial era (19th century), and major restoration work was performed by the National University of Singapore (NUS) in 2004. These CSHs are currently used as academic centres, and during the measurement period, they were occupied only on alternate weekdays from 10:00-17:00. Although the design of CSHs varies over different construction years, these CSHs are considered to be representative of typical shophouses from the Dutch colonial era.

House 1 had three courtyards, whereas House 2 had two courtyards, and their sizes increased from front to back (Fig.2.). The front courtyards (CY1s) and middle courtyards (CY2s) in both houses were deep atrium-

Table 1. Description of Measurement Instruments

Variable	Instrument model	Accuracy
Air temp. and RH at 1.5m	Vaisala HMP155, T&D TR-72U and HOBO U12-011	$\pm 0.10^{\circ}\text{C}$; $\pm 1.0\%\text{RH}$, $\pm 0.3^{\circ}\text{C}$; $\pm 5\%\text{RH}$ and $\pm 0.35^{\circ}\text{C}$; $\pm 2.5\%\text{RH}$
Vertical air temp.	Type T thermocouple, T&D TR-52 and HOBO U12-006	$\pm 0.1\% + 0.5^{\circ}\text{C}$ plus $\pm 0.5^{\circ}\text{C}$ for cold junction compensation, $\pm 0.3^{\circ}\text{C}$ and $\pm 0.25^{\circ}\text{C}$
Surface temp.	Type T thermocouple and T&D TR-52	$\pm 0.1\% + 0.5^{\circ}\text{C}$ plus $\pm 0.5^{\circ}\text{C}$ for cold junction compensation and $\pm 0.3^{\circ}\text{C}$
Globe temp.	Type T thermocouple inside 75mm and 150mm diameter black globes	$\pm 0.1\% + 0.5^{\circ}\text{C}$ plus $\pm 0.5^{\circ}\text{C}$ for cold junction compensation
Air speed	Kanomax 0965-03	$\pm 0.15 \text{ m/s}$
Outdoor air temp., RH and barometric pressure	T&D TR-73U	$\pm 0.3^{\circ}\text{C}$; $\pm 5\%\text{RH}$; $\pm 1.5 \text{ hPa}$



Fig.1. View of the Case Study Shophouses
(a) Front Façade; (b) Courtyard of House 1 (1-CY1);
(c) Courtyard of House 2 (2-CY1).

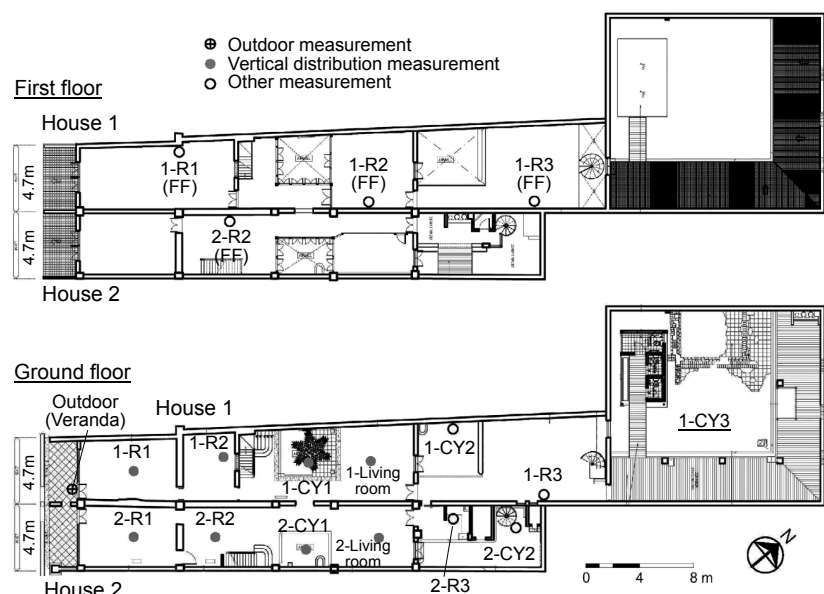


Fig.2. Floor Plans of the Case Study Shophouses
Note: Floor Plan with Permission of TTCLC, National University of Singapore

type courtyards surrounded by two-storey structures, and the rear large courtyard (1-CY3) was surrounded by a single-storey building. The front courtyards (CY1s) had measurements of 3.2 m by 3.9 m in House 1 and 2.6 m by 4.0 m in House 2 at the first floor level. The middle courtyards (CY2s) had larger dimensions, which were 3.9 m by 4.8 m in the case of House 1. The middle courtyard in House 2 was located at the end of the lot, and its configuration was different than that of the others (Fig.2.). Despite the sizes of the courtyards on the first floor level, the corresponding roof openings were smaller than the above sizes because of the roof overhangs that protected against rain and solar radiation. The size of the roof opening in the front courtyard of House 1 (1-CY1) was 2.6 m by 2.6 m, which was approximately 54% of the area of the courtyard below (see Fig.7.).

The windows in the two houses were composed of half-height timber panel windows with upper ventilation openings that were permanently open. These ventilation openings were also found on almost all of the interior partitions. The exterior door and windows were opened only on the ground floor in House 2 and the first floor in House 1 when the buildings were occupied (from 10:00-17:00 on alternate weekdays). Air conditioners were not installed, but ceiling fans were installed in most of the rooms. However, the ceiling fans were not used during the measurement period, except for the fan located in the living room of House 2, which was operated for a few hours during the daytime on three days (12/10, 14/10, 17/10). The building structures consisted of a timber frame and brick/concrete with lime plaster masonry walls. As shown in Fig.1.bc, the front courtyard of House 1 (1-CY1) had a tree and a terracotta brick floor, whereas the front courtyard of House 2 did not have plants and had a gravel floor surface (2-CY1).

The thermal conditions were measured at a height of 1.5 m above the floor in the centre of the living rooms in both CSHs, which is the location of the front courtyards (Fig.2.). As shown in Fig.1.bc, there were no partitions between the front courtyards and the surrounding spaces, (i.e., living rooms) on the ground floor; therefore, these living rooms were considered to be semi-closed spaces to the outdoors. The floor-to-ceiling height was approximately 4 m on the ground floor and approximately 3.5 m on the first floor in both of the houses. As shown in Fig.2., vertical temperature profiles were measured at several locations on the ground floor, which included the front courtyards. The air temperature and relative humidity were measured in several rooms in both of the houses. A weather station was located in an outdoor space approximately 500 m from the CSHs. The instrumentation that was used is shown in Table 1. All of the measurements were taken at 10-minute intervals.

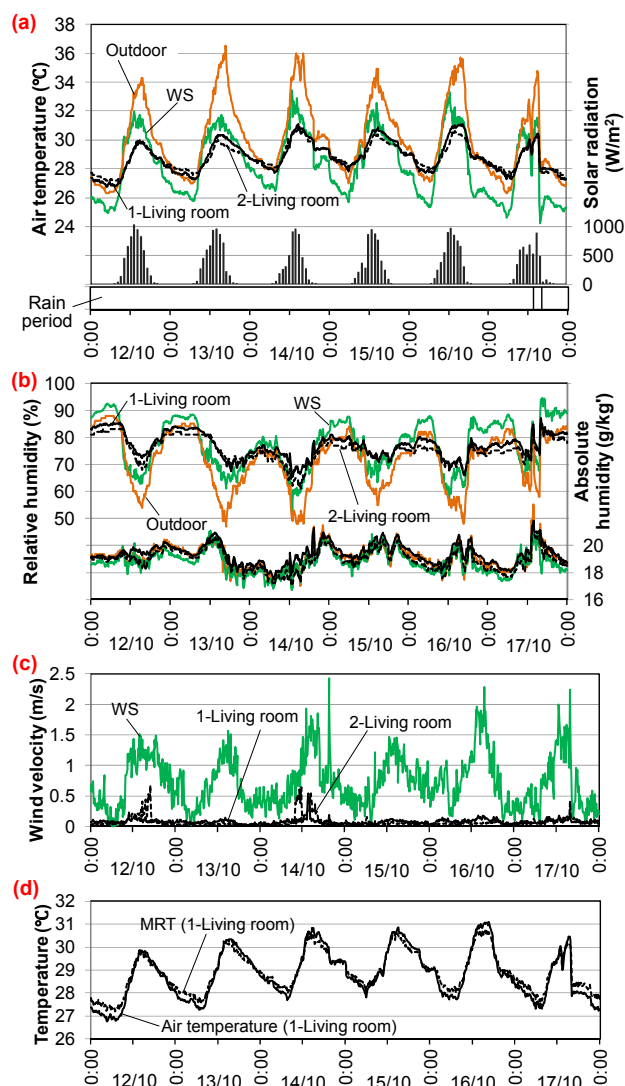


Fig.3. Temporal Variations of Major Thermal Variables in the Living Rooms (at 1.5m above floor) and the Outdoors (a) Air Temp. and Solar Radiation; (b) RH and AH; (c) Wind Velocity; (d) MRT (1-Living Room)

3. Results and Discussion

3.1 Evaluation of Thermal Comfort

Fig.3. shows the temporal variations of major thermal variables that were measured in the living rooms at a height of 1.5 m above the floor during the six-day measurement period. The outdoor conditions in this figure represent the values that were measured at the veranda located in front of House 1 (Outdoor) and the values that were measured at the weather station (WS). The veranda space was surrounded by man-made surfaces such as asphalt roads (Fig.2.) and thus reported higher temperatures throughout the day compared to the temperatures reported by the WS (Fig.3.a). Nevertheless, the measurements at the veranda space are representative of the immediate ambient environment, which is of interest for our data analysis. As shown in Fig.3.a, the daytime outdoor air temperature at the veranda reached a maximum temperature of approximately 34-36°C, and the air temperature at night dropped to approximately 26-28°C.

As shown in Fig.3.a, the indoor air temperature in both houses was approximately 5-6°C lower than the immediate outdoor temperature during the daytime. At night, the indoor air temperature in both houses was similar to the outdoor temperature. The cooling effect caused by the tree in the front courtyard of House 1 (1-CY1) cannot be observed in this figure. The measured relative humidity was high throughout the day in both of the houses (Fig.3.b). The absolute humidity in House 1 was slightly higher than that in House 2 by approximately 1 g/kg, which is most likely due to transpiration of the tree in the front courtyard. This increased absolute humidity resulted in a higher relative humidity in House 1 compared to House 2 (Fig.3.b). The relative humidity in House 1 during the day ranged from 65-70%, whereas the relative humidity at night was approximately 75-85%.

The average measured wind velocities at the weather station, which was located in an open space near the case study site, were approximately 0.9 m/s during the daytime and approximately 0.5 m/s at night (Fig.3.c). Despite the outdoor wind velocities, the corresponding indoor air velocities in the living rooms of both houses exhibited calm conditions (less than 0.1 m/s) throughout the day, except when the ceiling fan was used in House 2. This result indicates that both living rooms had minimal cross ventilation, even if the exterior door or windows were open. The indoor air velocity increased to approximately 0.6 m/s when the ceiling fan was operated in the living room of House 2.

As previously described, these CSHs consisted of brick-walled structures that have relatively high thermal capacities. Therefore, the diurnal ranges of surface temperatures of the indoor building structures were smaller than the range of ambient air temperatures (Figs.9.-10.). Accordingly, the mean radiant temperatures in the living rooms were slightly less than the ambient air temperatures during the daytime and slightly greater at night (Fig.3.d).

Fig.4. shows the results of the thermal comfort evaluation. ASHRAE (2010) proposes an optional standard required for spaces that are naturally conditioned, which is called the Adaptive Comfort Standard (ACS). The houses in this case study are considered to be naturally conditioned. The thermal comfort evaluation was performed based on the ASHRAE ACS. The acceptable operative temperature limits from the ACS were determined based on the

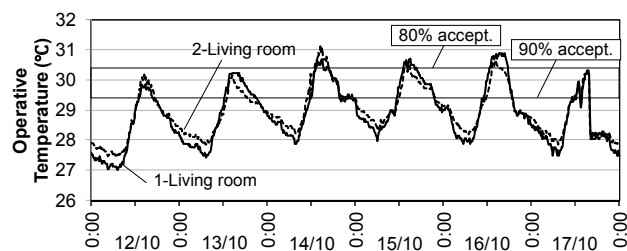


Fig.4. Results of Thermal Comfort Evaluation in Living Rooms (at 1.5m above floor)

measured outdoor air temperature. The measured operative temperatures were within the 80% acceptable range for most of the period in the living rooms of both houses (Fig.4.). If the thermal adaptations of the occupants were accounted for, then the thermal conditions in the living rooms were acceptable for most of the day.

3.2 Thermal Environment Variations in Entire House

Fig.5. shows the average air temperatures in different spaces during fair weather days. The air temperature data displayed at the top of the line charts represent the average air temperatures on the first floor in House 1. Fig.6. also shows a statistical summary of the air temperature and humidity in the selected spaces in House 1.

As shown in Fig.5.a, at 6:00, the indoor air temperatures were nearly the same as the outdoor temperature (27.2°C). A slightly warmer air temperature of 28.5°C was observed in R1 of House 2. The difference of air temperature among spaces increased from the late morning (Fig.5.b). As shown in Fig.5.bc, on average, the indoor air temperatures on the ground floor in both houses were 2-3°C lower than the outdoor temperature at 12:00 and 3-4°C lower at 15:00, which is primarily due to the effect of thermal mass. The heavyweight structures were cooled at night, which reduced the indoor air temperatures during the day. This effect is well known in high thermal mass buildings that are ventilated at night (Kubota *et al.*, 2009), and it is interesting to observe this effect even with the open courtyards that were located nearby such as the living rooms. The average air temperatures in R1 and R2 of House 2 were approximately 1°C higher than the corresponding temperatures in House 1 during this period, which is primarily because the front main door was only open in House 2 from 10:00-17:00, as previously described.

As shown in Fig.5.bc, the air temperatures in the front courtyards of both houses (CY1s) were nearly the same as the temperature of the surroundings in the afternoon. Nevertheless, the average air temperatures in the middle courtyards (CY2s) were approximately 1-6°C higher than the temperature of the surroundings, which indicates that the size of the courtyard significantly affects its air temperature. Fig.7. presents horizontal sun-path diagrams of each courtyard on the measurement day. The roof overhangs effectively provided shade to each courtyard, except for CY2 in House 2. The tree located in CY1 of House 1 also provided shade to the courtyard. As shown in the sun-path diagrams, both CY1s in Houses 1 and 2 received minimal direct solar radiation (less than one hour at approximately 13:00) on the measurement day. The CY2 in House 1 received less than 2 hours of direct solar radiation between 12:00 and 14:00. The CY2 in House 2 had the highest temperatures among the four courtyards because it received direct solar radiation for 2 hours or more from 12:00-14:00.

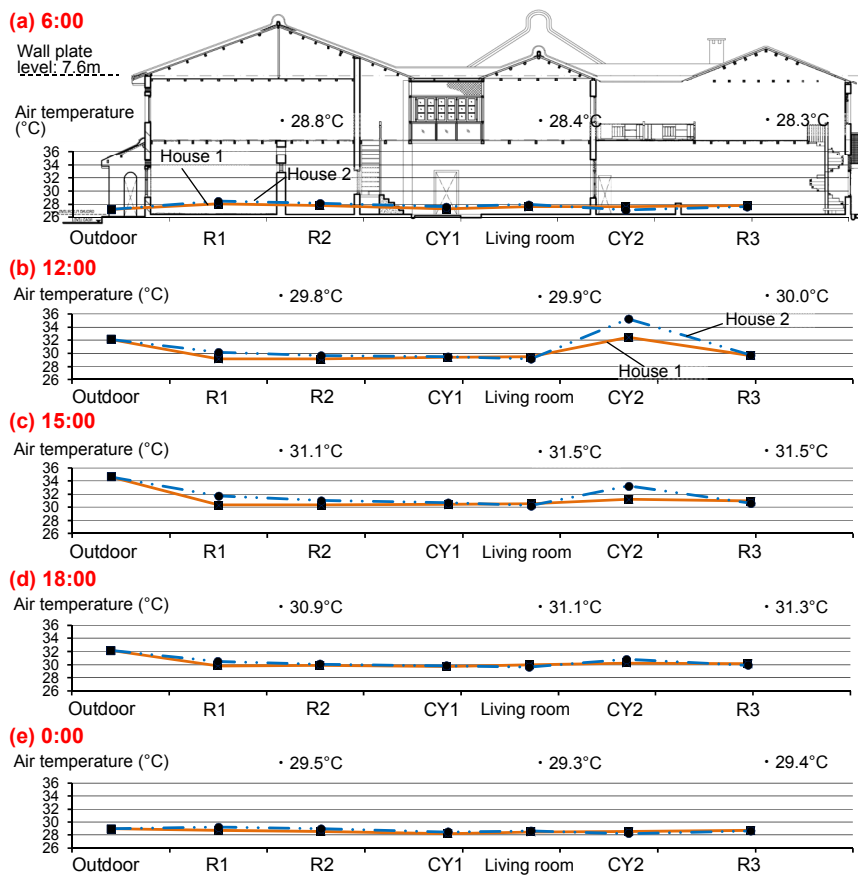


Fig.5. Averaged Air Temperatures in Different Spaces (at 1.5m above floor)
(a) 6:00; (b) 12:00; (c) 15:00; (d) 18:00; (e) 0:00.

Note: Section with Permission of TTCLC, National University of Singapore

Fig.8. shows the relationships between the sky view factors of the courtyards and their air temperatures (at a height of 1.5 m above floor). Although the results are not necessarily statistically valid due to their small sample size, there are strong relationships between the two variables, particularly in terms of daily peak air temperature (i.e., 95th percentile values) and mean values. A reduction in the sky view factor of a courtyard reduces its air temperature. As shown in Fig.6.a, CY1 had lower air temperatures than CY2 in terms of daily peak and mean values in House 1. The above mean was the lowest value among all of the indoor spaces of House 1 (28.7°C), which indicates that CY1 functioned as a cooling source for the surrounding spaces.

As shown in Fig.5.de, the indoor air temperatures gradually declined from day to night by approximately 2°C, except for the temperatures in the middle courtyards (CY2s). The indoor air temperatures (including those in the front and middle courtyards) dropped to approximately 28.5°C at 0:00, which was approximately the same value as the outdoor temperature.

3.3 Vertical Air Temperature Profiles

Fig.9. shows the vertical temperature profiles at various points on the ground floor in the two houses. Fig.10. shows the temporal change of the vertical distribution in the living room and the front courtyard (CY1) in House 1. As shown in Figs.9.a and 10.a, the

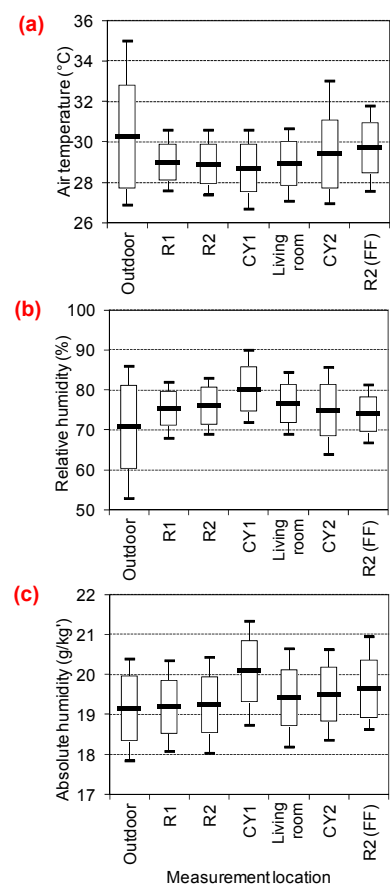


Fig.6. Statistical Summary
(5th and 95th Percentiles, mean and \pm one s.d.)
of Measurements in House 1
(at 1.5m above floor) (a) Air Temperature;
(b) Relative Humidity; (c) Absolute Humidity

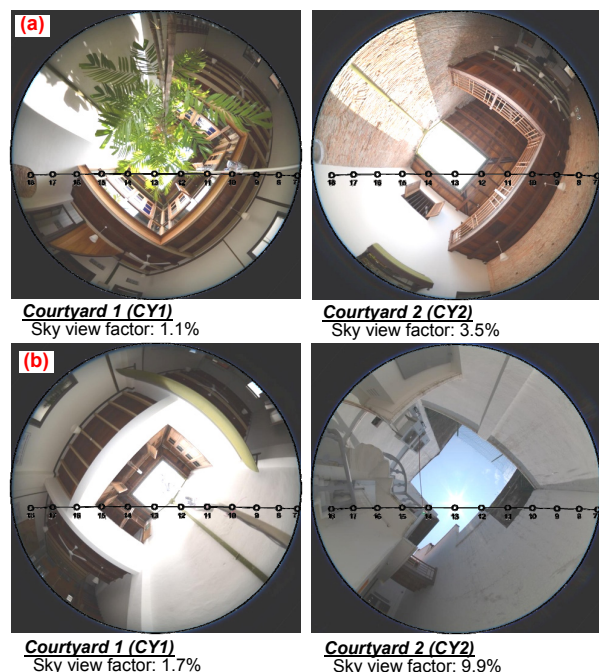


Fig.7. Horizontal Sun-Path Diagrams of Courtyards on 15 October
(a) House 1; (b) House 2.

Note: Fisheye photos were taken at 1.5m above floor at the approximate center of courtyards using an equisolid-angle projection lens. The top of photos is directed to the North.

surface temperature of the building structures (i.e., ceilings and floors) of both houses was approximately 1°C lower than the ambient air temperatures at 15:00 due to the structural cooling effect through using night ventilation. In CY1s, the air temperatures at a height of 1.5 m were 1-2°C lower than the temperatures at the higher levels and approximately 4°C lower than the outdoor temperature at 15:00 (Figs.9.a and 10.b). The air temperatures in CY1s increased along with height. For House 1, the surface temperature and air temperature at the lower levels were well cooled by the tree and wet ground surface, which emphasised the above temperature gradient. This temperature gradient caused thermal stratification in the above courtyards and prevented vertical air exchange. This effect was most likely one of the primary causes of the relatively lower air temperatures during the daytime in the front courtyards and their adjacent spaces despite hot outdoor conditions.

However, the above temperature gradient was not observed at night, except for the surface temperature of CY1 in House 1 (Figs.9.b and 10.b). This result indicates that vertical air exchange occurred in this case, and thus the indoor air temperatures were sufficiently reduced to outdoor levels. Figs.9.b and 10.a show that the surface temperatures of the building structures in both houses were up to 1°C higher than the temperatures at a height of 1.5 m at night. This result indicates that relatively cool outdoor air (which was approximately 27-29°C) most likely entered the buildings not only from the ventilation openings on

the exterior walls but also from the upper openings of the courtyards and effectively cooled the building structures at night. Additionally, the air cooled by nocturnal radiant cooling above the pitched roofs most likely flowed into the courtyards and further reduced the indoor air temperature. As a result, the indoor air temperatures were lower on the following day (i.e., nocturnal structural cooling).

4. Comparative Analysis with Modern Terraced Houses

A previous field measurement study was conducted by the authors (Kubota *et al.*, 2009) in two adjacent terraced houses in the city of Johor Bahru, Malaysia,

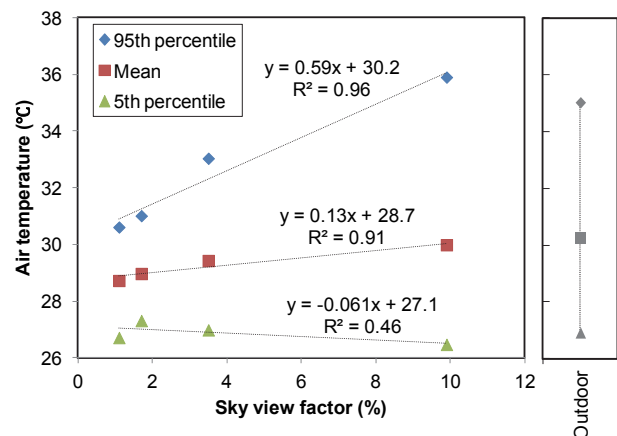


Fig.8. Relationships between Sky View Factors of Courtyards and their Air Temperatures (at 1.5m above floor)

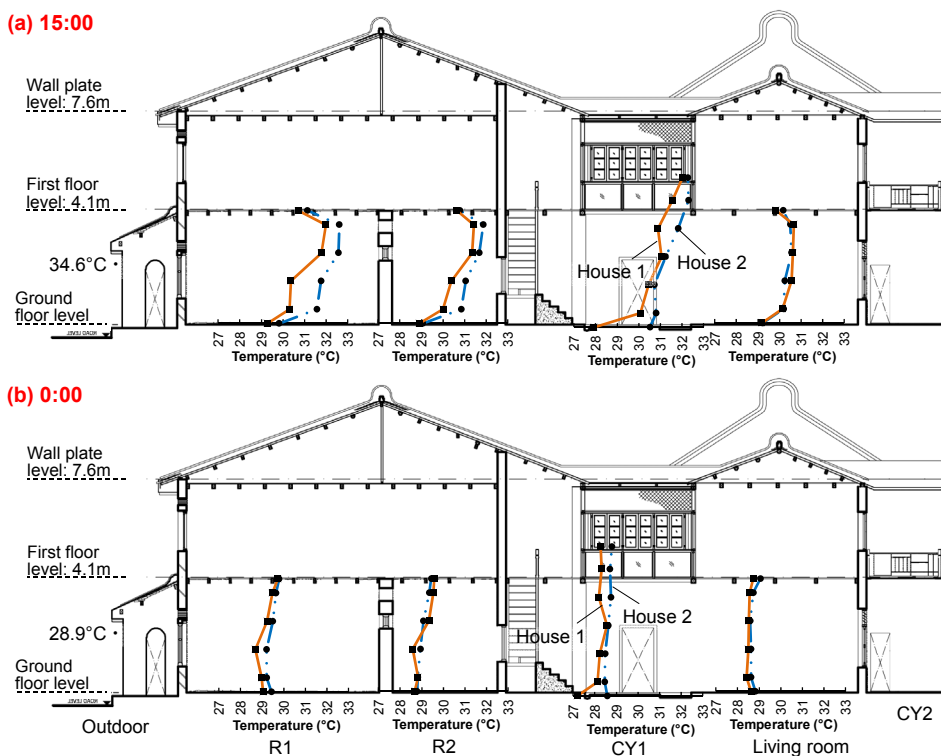


Fig.9. Vertical Air Temperature Profiles on the Ground Floor. (a) 15:00; (b) 0:00
 Note: Section with Permission of TTCLC, National University of Singapore

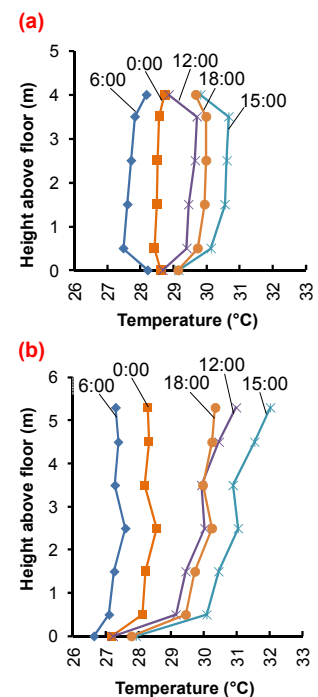


Fig.10. Temporal Change of Vertical Air Temperature Profiles
 (a) 1-Living Room; (b) 1-CY1

from June 2007 to August 2007 to examine the effects of various ventilation strategies such as daytime ventilation and night ventilation (Fig.11.). Daytime ventilation was achieved by opening all of the windows from 8:00-20:00 and closing them from 20:00-8:00 to emulate the window opening behaviour of the household that was observed in the previous survey (Kubota *et al.*, 2009). For night ventilation, all of the windows were closed from 8:00-20:00 and open from 20:00-8:00. Terraced houses are considered to be the most common type of modern urban houses in Malaysia (DSM, 2005). The houses were constructed of brick and concrete with a relatively high thermal capacity similar to CSHs, and each elongated row house measured 6.7 m by 13.1 m.

Figs.12.-13. present scatter plots of indoor and outdoor air temperatures and relative humidity based on the measured data on fair weather days in the traditional CSHs and terraced houses. In the case of CSHs, the measured data in the living rooms represent the indoor conditions. The results of a regression analysis indicate that the daily peak indoor air temperatures in the CSHs were lower than the outdoor temperature by approximately 5-6°C, whereas the air temperatures at night were similar to the outdoor temperature (Fig.12.a). However, the indoor relative humidity was higher than the outdoor relative humidity for most of the day (Fig.12.b). The relative humidity

was never below 60% in the living rooms of the CSHs.

The results of the terraced houses also reflected the high thermal mass effects of the brick-walled structures. As observed in the CSHs, the peak indoor air temperatures were lower than the outdoor temperature whether daytime ventilation or night ventilation was applied (Fig.13.a). Nevertheless, the nocturnal indoor air temperatures were approximately 1-2°C higher than the outdoor temperature even under the night ventilation conditions.



Fig.11. View of the Case Study Terraced Houses
Source: Kubota *et al.* (2009)

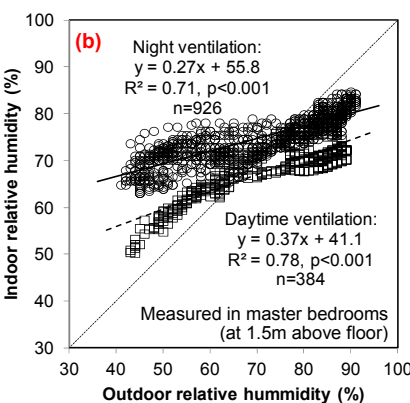
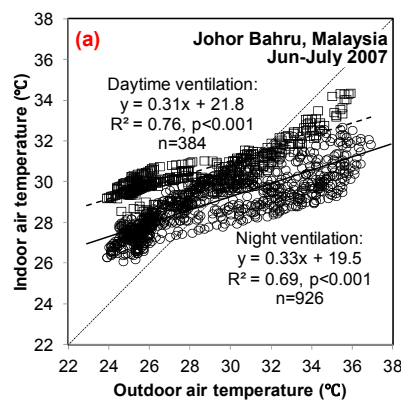
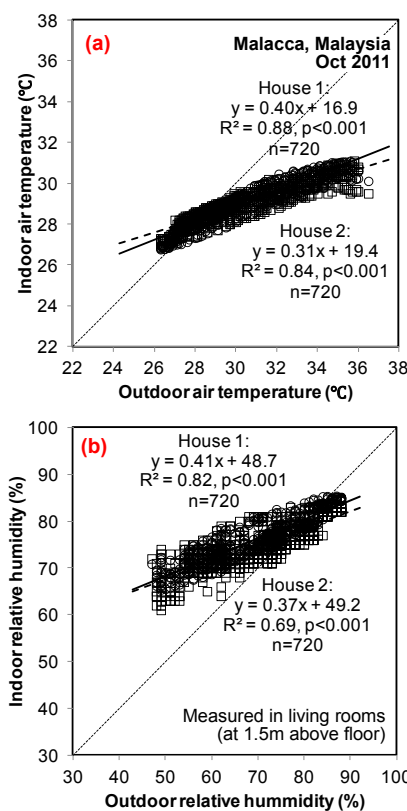


Fig.13. Relationship between Indoor and Outdoor Measurements in Terraced Houses on Fair Weather Days
(a) Air Temperature; (b) Relative Humidity

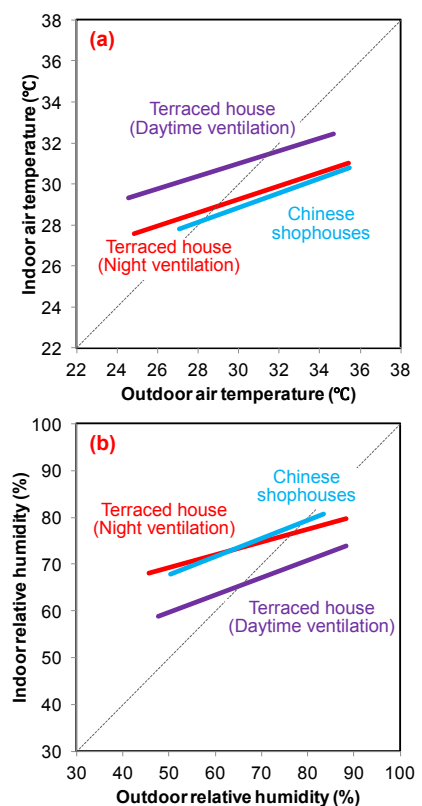


Fig.14. Comparison between CSHs and Terraced Houses
(a) Air Temperature; (b) Relative Humidity

Fig.14. shows regression lines that were obtained from Figs.12.-13. As shown in Fig.14.a, the trend line of the CSHs indicates a cooling performance during the daytime that was similar to the terraced houses with night ventilation. When the daily maximum outdoor air temperature is 35.5°C, both houses are expected to reach indoor air temperatures of approximately 31°C. When the daily minimum air temperature is 27.0°C, the indoor temperature of the CSHs is predicted to be approximately 27-28°C, whereas the indoor temperature of the terraced house is approximately 28.5°C. This result indicates that the CSHs with courtyards achieved similar or slightly better cooling effects at night compared to the terraced houses with night ventilation, even though the windows on the exterior walls were closed.

The results from the previous survey indicated that a majority of the respondents living in terraced houses did not open windows at night because of security concerns (Kubota *et al.*, 2009). Therefore, the application of courtyards to modern terraced houses is one possible means of achieving sufficient cooling effects through using night ventilation without opening windows.

5. Conclusions

The conclusions for this study can be summarised as follows:

(1) Indoor air temperatures in the living rooms of both CSHs were significantly lower than the immediate outdoor temperature during the day by approximately 5-6°C, whereas the indoor air temperatures at night were similar to the outdoor temperature. If the thermal adaptations of the occupants were considered by using ASHRAE ACS, then the thermal conditions in the living rooms were acceptable for most of the day. However, the relative humidity was never below 60% in the living rooms during the measurement period.

(2) The daily mean air temperatures in the front courtyards were the lowest among all of the spaces in both CSHs. This result indicates that the front courtyards functioned as a cooling source to the surrounding spaces. There was a strong relationship between the sky view factors of the measured courtyards and their air temperatures, particularly in terms of daily peak air temperature and mean values. A reduction in the sky view factor of a courtyard reduced its air temperature.

(3) Air temperatures in the front courtyards increased along with height during the afternoon. This temperature gradient caused thermal stratification in the courtyards, which prevented vertical air exchange. This effect was most likely one of the primary causes of relatively lower air temperatures during the day in the front courtyards and their adjacent spaces, despite hot outdoor conditions. However, the temperature gradient was not observed at night.

(4) The CSHs with courtyards exhibited a cooling performance similar to modern terraced houses during the day. Meanwhile, the CSHs achieved similar or

slightly better cooling effects at night compared to the terraced houses with night ventilation, even though the windows on the exterior walls were closed. The application of courtyards to modern terraced houses could be one possible means of achieving sufficient cooling effects through using night ventilation without opening windows.

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References

- 1) Al-Hemiddi, N.A., Al-Saud, K.A.M. (2001) The effect of a ventilated interior courtyard on the thermal performance of a house in a hot-arid region, *Renewable Energy* 24, pp.581-595.
- 2) ASHRAE (2010) ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta.
- 3) Berkovic, S., Yezioro, A., Bitan, A. (2012) Study of thermal comfort in courtyards in a hot arid climate, *Solar Energy* 86, pp.1173-1186.
- 4) Chen, V.F. (ed) (1998) *The Encyclopedia of Malaysia*, Vol. 5, Architecture, Archipelago Press.
- 5) Department of Statistics Malaysia (DSM) (2005) General Report of the Population and Housing Census 2000, Department of Statistics Malaysia.
- 6) Dili, A.S., Naseer, M.A., Zacharia, Varghese, T. (2011) Passive control methods for a comfortable indoor environment: comparative investigation of traditional and modern architecture of Kerala in summer, *Energy and Buildings* 43, pp.653-664.
- 7) Edwards, B., Sibley, M., Hakmi, M., Land, P. (ed) (2006) *Courtyard Housing: Past, Present & Future*, Taylor & Francis.
- 8) Japan Meteorological Agency (JMA): World Weather Information Service, < <http://www.data.jma.go.jp/gmd/cpd/monitor/> > (accessed on 4 March 2013)
- 9) Knapp, R.G. (1999) *China's Old Dwellings*, University of Hawai'i Press, Honolulu.
- 10) Kubota, T., Toe, D.H.C., Ahmad, S. (2009) The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia, *Energy and Buildings* 41(8), pp.829-839.
- 11) Kubota, T., Toe, D.H.C. (2012) Cooling effects of courtyards in traditional Chinese shop houses in Malacca, Summary of Technical Papers of Annual Meeting, AIJ, Vol.D1, pp.539-540.
- 12) Oliver, P. (2006) *Built to Meet Needs: Cultural Issues in Vernacular Architecture*, Architectural Press, Oxford.
- 13) Park, H.J., Park, Y.K. (2010) Revitalization of environmental sustainability hidden in Yeongyeongdang, *J. of Asian Architecture and Building Engineering*, 9(2), pp.291-298.
- 14) Rajapaksha, I., Nagai, H., Okumiya, M. (2002) Indoor thermal modification of a ventilated courtyard house in the tropics, *J. of Asian Architecture and Building Engineering*, 1(1), pp.87-94.
- 15) Rajapaksha, I., Nagai, H., Okumiya, M. (2003) A ventilated courtyard as a passive cooling strategy in the warm humid tropics, *Renewable Energy* 28, pp.1755-1778.
- 16) Tablada, A., De Troyer, F., Blocken, B., Carmeliet, J., Verschure, H. (2009) On natural ventilation and thermal comfort in compact urban environments – the Old Havana case, *Building and Environment* 44, pp.1943-1958.
- 17) Toe, D.H.C., Kubota, T. (2013) Field measurement on thermal comfort in traditional Malay houses, *AIJ Journal of Technology and Design*, 19(41), pp.219-224.
- 18) Upadhyay, A.K., Yoshida, H., Rijal, H.B. (2006) Climate responsive building design in the Kathmandu Valley, *J. of Asian Architecture and Building Engineering*, 5(1), pp.169-176.